separated by a dielectric sheet", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 172–185, Mar. 1965.
[12] M. Ogawa, K. Ohata, T. Furutsuka, and N. Kawamura, "Submicron single-gate and dual-gate MESFET's with improved low noise and high gain performance," *IEEE Trans. Microwave Theory Tech.*, vol. MTT- 24, pp. 300–305, June 1976.
[13] M. M. Nowak, P. A. Terzian, and R. D. Fairman, "K-band F.E.T. amplifiers," *Electron. Lett.*, vol. 13, pp. 159–160, Mar. 1977.

Frequency Tuning of Microstrip TRAPATT Oscillators

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***Abstract*—This paper describes two methods of magnetically tuning the frequency of a microstrip TRAPATT oscillator. Tuning ranges in excess of 100 MHz at a center frequency of 2 GHz have been obtained at peak output power levels of typically 40 W with variations in output power of ±0.2 dB. In one of the methods the harmonics of the oscillator are separated which may enable additional diagnostic information to be obtained for the TRAPATT oscillator.**

I. Introduction

THE TRAPATT oscillator is now being evaluated as the transmitter unit in compact, all solid-state pulsed radar sets. If frequency agility is required it becomes necessary to study methods of tuning a TRAPATT oscillator. This paper describes two methods for moderate tuning rates which involve the use of a variable external magnetic field. Since the required field change in each method is relatively small, the rate of change of frequency may be as fast as several tens of megahertz per microsecond. The first method uses the change of the effective permeability of a ferrite substrate created by varying an applied magnetic field to change the electrical length of the triggering section of a microstrip TRAPATT oscillator. The second and preferred method changes the phase of selected harmonics of a microstrip TRAPATT oscillator by varying the ferrimagnetic resonance of a suitably biased and positioned garnet sphere. Both methods of tuning use the same basic TDT (Time Delay Triggered) type of microstrip oscillator already described [1], [2].

II. Tuning by Variation of Effective Permeability

Permeability tuning was first investigated by Glance [3] for the tuning of IMPATT oscillators and later by Liu [4] for TRAPATT oscillators. The oscillator is of the TDT type whose oscillation frequency is determined mainly by the electrical length of the low-impedance triggering line [1]. Since the electrical length is a function of the permittivity and permeability of the substrate material, it follows that the line may be tuned if either of these material parameters can be adjusted. By defining the TRAPATT circuit on a microwave ferrite substrate it is possible to vary the electrical length of the triggering line via the change in the permeability induced by applying a small, variable, magnetic field in the plane of the substrate. The construction of the prototype oscillator is shown in Fig. 1.

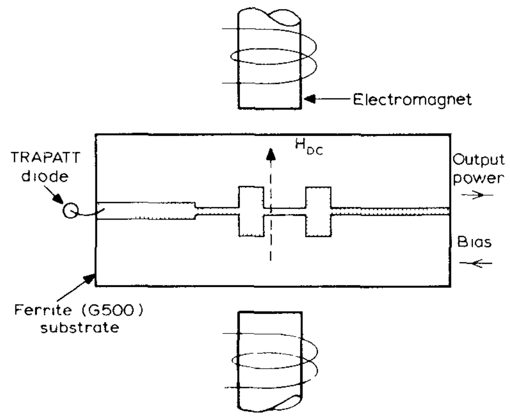

Fig. 1. Schematic of magnetically tuned TRAPATT oscillator.

The results obtained by applying a small magnetic field whose angular direction could be changed perpendicular to the direction of propagation in the microstrip line (see Fig. 1) are given in Fig. 2. The parameter on the graph is the angle between the normal to the magnetic field direction and the plane of the substrate. It can be seen that an optimum tuning range of approximately 60 MHz was obtained from an initial frequency ($H=0$) of 2.19 GHz. The corresponding power versus field variation is shown in Fig. 3. The output power remained substantially flat (13 W peak ±0.5 dB) over this frequency range and the

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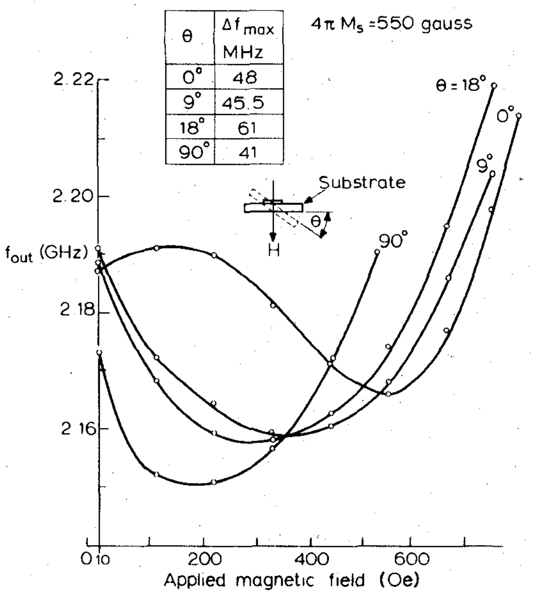


Fig. 2. Variation of frequency with external magnetic field.

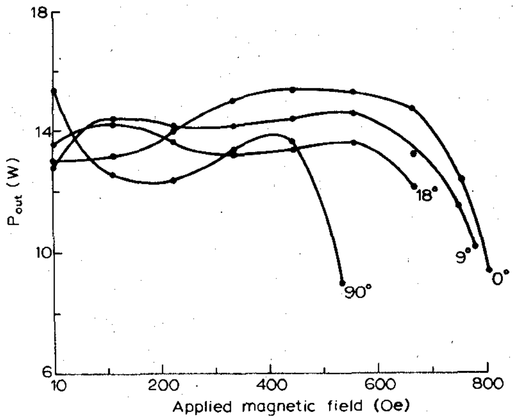


Fig. 3. Variation of output power with external magnetic field.

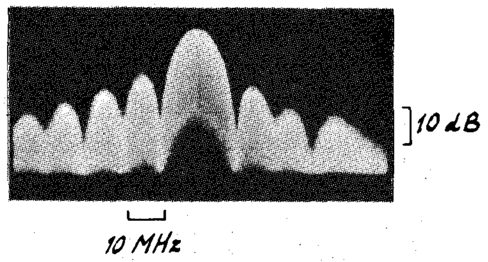


Fig. 4. Output spectrum of TRAPATT oscillator.

frequency spectrum was clean and symmetrical (see Fig. 4). The field variation required was found to be typically zero to 800 Oe. The shape of the tuning curves is different from that noticed by Liu and a qualitative explanation is offered below. The tuning range however is in broad agreement.

A. Discussion of the Results.

The tuning curves of Fig. 2 show a pronounced "dip" and are very nonlinear. A qualitative explanation of the

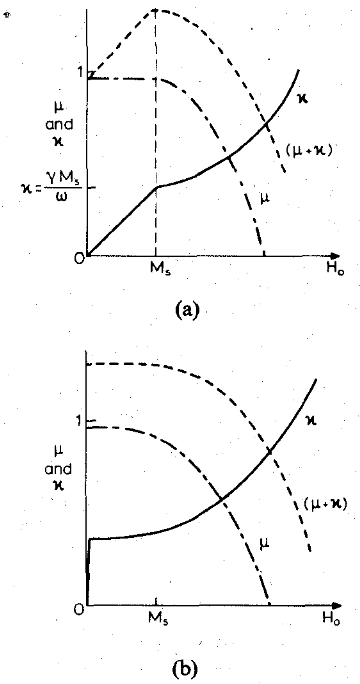


Fig. 5. Sketch of possible variation of effective permeability for the magnetized substrate of Fig. 2. (a) Case of $\theta=0$ where $H_i=H-M$. (b) Case of $\theta=90$ where $H_i=H$. Components of tensor permeability are $\mu=1+\gamma^2MH_i/\omega^2-\gamma^2H_i^2$; $\kappa=\omega\gamma M/\omega^2-\gamma^2H_i^2$.

shape of the frequency–magnetic field curves is possible if the demagnetization effect of the substrate is considered. For the substrate the internal magnetic field H_i is related to the applied field H through the expression

$$H_i=H-NM \tag{1}$$

where M is the magnetization and N is the demagnetizing factor. N is a function of the orientation of the field to the substrate and for $\theta=0°$, $N\approx1$ and $\theta=90°$, $N\approx0$. Consequently, it is possible that the components μ and κ of the effective permeability tensor $\vec{\vec{\mu}}_e$ vary as in Fig. 5(a) and 5(b) for magnetization perpendicular and parallel to the ferrite broad surface, respectively. The TRAPATT oscillation frequency f is related to the length of the triggering line L as follows:

$$L\approx\frac{\lambda_m}{2}\approx\frac{\lambda_0}{2(\mu_e\epsilon_e)^{1/2}}\approx\frac{c}{2f(\mu_e\epsilon_e)^{1/2}}$$

where λ_m = wavelength on the ferrite, λ_0 = free space wavelength, and c = velocity of EM propagation. If L is fixed and μ_e varied, then

$$f\propto(\mu_e)^{-1/2}. \tag{2}$$

In practice the effective permeability μ_e will be a complex function of μ and κ but it can be seen that it is possible to predict a peak in the value of μ_e (for example, the simple case of $\mu_e=\mu+\kappa$) at the saturation field and hence a minimum in the value of the TRAPATT frequency according to (2). This effect is seen in the practical results of Fig. 2 where a minimum occurs at approximately the field for saturation $H=4\pi M_s=550$ Oe.

III. Tuning by Means of Ferrimagnetic Resonators

Wide tuning of fundamental microwave oscillators (Gunn, IMPATT, and transistor) at relatively low power levels (<200 mW) has been realized previously using single crystal yttrium iron garnet (YIG) spheres as the magnetically tuned resonator. However, it is well known that ferrimagnetic materials exhibit nonlinear effects which restrict the power output from the oscillators [7]. The maximum permitted signal level at the magnetic sphere depends upon frequency, in general being smaller for lower frequencies, and upon magnetic parameters, being particularly small for YIG because of its very small resonance and spin-wave linewidths. The power handling capability can be increased by using materials with larger linewidths than YIG and by coupling the sphere to one of the harmonics of the oscillator. However, increasing the material resonance linewidth has the disadvantage of decreasing the value of unloaded Q-factor which increases circuit losses. A compromise material has therefore to be used and a promising one [8] is a *polycrystalline* doped garnet with composition $Y_{2.6}Ca_{0.4}Fe_{4.2}In_{0.6}V_{0.2}O_{12}$ and the following parameters: $4\pi M_s = 1440$ G; $\Delta H = 1.5-2.0$ Oe; $\Delta H_k = 0.74$ Oe; Curie Temperature $T_c = 160°$C.

The limiting at low frequencies can be avoided by tuning at a harmonic of the TRAPATT fundamental frequency. Trew *et al.* [5], [6] have indicated from their computer simulation studies of the TRAPATT device that frequency tuning is possible by varying both the amplitude or phase of the fundamental, second, third, or fourth harmonic load impedances.

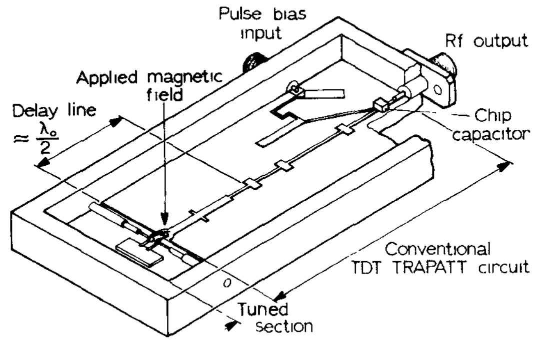
A. Potential for TRAPATT Tuning (Using $Y_{2.6}Ca_{0.4}Fe_{4.2}In_{0.6}V_{0.2}O_{12}$

1) It is desirable that the tuning frequency (fundamental or harmonic) should exceed 2.7 GHz to avoid the coincidence limiting effect with its associated very low power threshold level [7].

2) Operation at higher harmonic frequencies allows higher unloaded Q-factors for the resonator as the resonance linewidth is largely independent of frequency.

3) Power at the fundamental frequency can easily be decoupled from the ferrite resonator by simple circuit techniques.

To achieve a practical oscillator, a 0.93-mm diameter polycrystalline garnet sphere of the above composition was semiloop coupled approximately one quarter of a wavelength from the open circuit end of an air-spaced microstrip transmission line connected in shunt with the TRAPATT diode chip. The TRAPATT diode was also connected in shunt with a TDT, MIC oscillator circuit on alumina as previously reported [1]. The magnetic field required to tune the ferrimagnetic resonator, which primarily controls the operating frequency, was applied perpendicular to the substrate and parallel to the plane containing the semiloop. Both single and double garnet resonators were used in the experiments and the sketch in



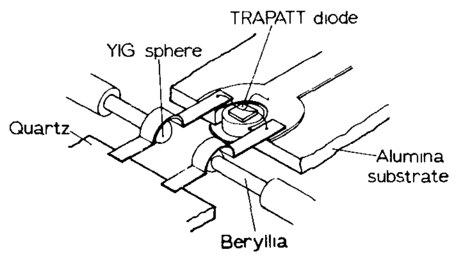


Fig. 6. Double YIG sphere tunable TRAPATT oscillator.

Fig. 6 illustrates the basic construction of the double-sphere unit. The basic oscillator is built onto 0.5-mm thick alumina substrate with nichrome–gold metallization (described in [1]). The oscillator was adjusted for the widest tuning range using the adjustable low-impedance sections at the appropriate bias field. Fine adjustments between the sphere(s) and the diode were also made to optimize the range.

B. Results

1) Single Sphere Resonator: Using this method, a fundamental frequency tuning range in excess of 90 MHz at a center frequency of 2.4 GHz was obtained by biasing the sphere to resonate near the third harmonic. The tuning curves for power and frequency are illustrated in Figs. 7 and 8 for third and second harmonic tuning, respectively.

2) Double Sphere Resonator: Using an identical magnetic resonator circuit in parallel with the first resonator circuit (Fig. 6), a broader tuning range was measured (127 MHz, 5 percent) (Fig. 9) due to the improved coupling. This circuit has the additional benefit of higher power handling because power at the harmonic frequency is shared between the two spheres. A summary of the results for third harmonic tuning is given in Table I, and Table II indicates results of tuning at the second, fourth, and third harmonics, the latter using short circuited semiloop coupling. The experiments were performed under the following conditions; pulsewidth$\approx$300 ns, duty cycle$\approx$0.1 percent, peak current$\approx$3 A, peak voltage$\approx$70 V.

C. Discussion

Figs. 7, 8, and 9 show that the tuning characteristics are not linear. (The slope for a ferrimagnetic resonator

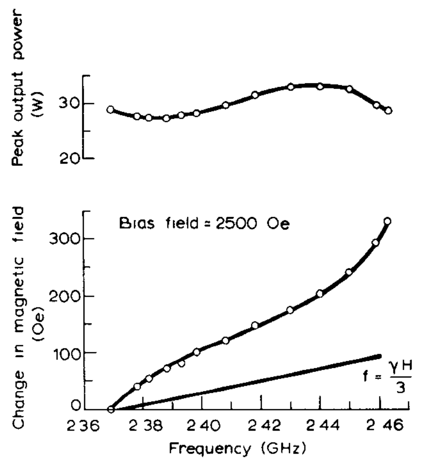


Fig. 7. Single sphere tuning of the third harmonic of the TRAPATT.

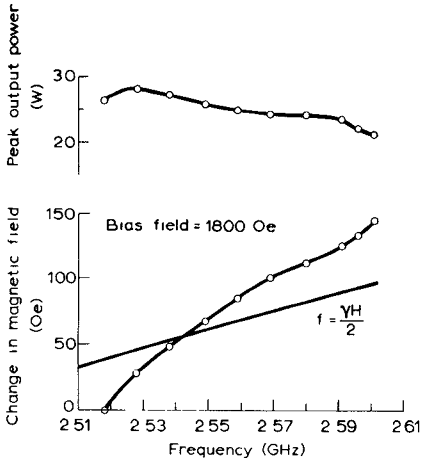


Fig. 8. Single sphere tuning of the second harmonic of the TRAPATT.

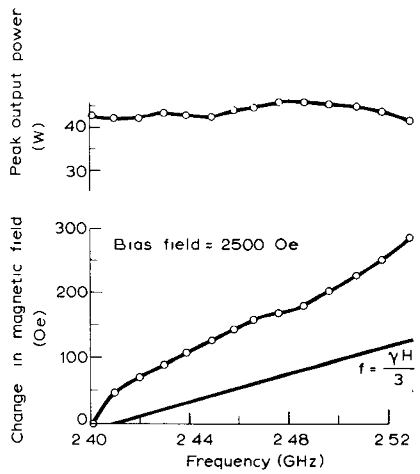


Fig. 9. Double sphere tuning of the third harmonic of the TRAPATT.

alone is included for comparison.) This is not too surprising, since the requirements that all resonant circuits except the YIG sphere resonance are well removed in frequency from the region of operation cannot easily be satisfied because the appropriate terminations of the fundamental and other nonmagnetically tuned harmonics have to be maintained for efficient TRAPATT action. However, the tuning is reasonably linear over a substantial part of the characteristic.

TABLE I
RESULTS FOR THIRD HARMONIC TUNING

Center Freq. f_c (MHz)	Δf (MHz)	Power Out (W)	Mean Efficiency (%)	M*	Δ field (Oe)
a) Single Sphere					
2393	26	67W±.2 dB	23	0.25	84
2434	94	39W±.6 dB	13.8	0.53	427
2416	94	30W±.4 dB	13.2	0.51	323
2395	51	49W±.4 dB	18.2	0.39	148
2407	81	39W±.4 dB	13.9	0.47	174
b) Double Sphere					
2370	108	40W±.5 dB	15.0	0.68	313
2465	127	43W±.2 dB	14.3	0.74	287

*M = $\frac{\Delta f}{f_c}$ x Eff% = figure of merit (M) = normalized freq. tuning x DC to RF conversion efficiency.

The results tabulated above refer to the output from an MIC oscillator on alumina at the fundamental frequency.

TABLE II
RESULTS FOR SECOND, THIRD, AND FOURTH HARMONIC TUNING

Harmonic Number	Sphere Position (single)	Center Frequency (GHz)	Δf (MHz)	Power Out (W)	Mean Eff. (%)	M*	Δ field (Oe)
2nd	$\frac{\lambda_2}{4}$ O/C	2.56	83	24.1 ±0.5	11.6	0.38	145
4th	$\frac{\lambda_4}{4}$ O/C	1.89	35	37.1 ±0.1	19.3	0.36	-
3rd†	S/C	2.46	60	40.8 ±0.15	15.8	0.39	632

† This circuit showed some tuning at magnetic bias corresponding to the 2nd harmonic resonance as well as the desired 3rd harmonic.

IV. CONCLUSIONS

The following conclusions can be extracted for the two tuning methods.

A. Permeability Tuning

The experiments demonstrate that this method provides a satisfactory tuning range; a maximum range of 60 MHz was achieved with a modest change in field. The characteristics are somewhat nonlinear and depend upon the orientation of the magnetic bias field. The shape of the tuning curves appears to be related to the variations in the effective permeability of the ferrite material.

B. Polycrystalline YIG Harmonic Tuning

This method provided larger tuning ranges than the previous method with improved linearity. The method is novel and demonstrates the feasibility of individually tuning the harmonics of a TRAPATT oscillator. The best tuning range was obtained (127 MHz at 2.4 GHz) by tuning the third harmonic with a double-sphere arrangement. The output power was 40 W peak ±0.2 dB over the

TABLE III
COMPARISON OF MEASURED OSCILLATOR PERFORMANCE WITH COMPUTATIONS OF TREW *et al.*

	2nd Harmonic		3rd Harmonic	
	Measured	Computed	Measured	Computed
Tuning Range %	3.2	3.8	5.1	17.2
Efficiency Variation (dB)	±0.5	±1.0	±0.3	±0.6
Phase Shift of Harmonic	-	45°	100-150	100

range. Table III shows qualitative agreement with previously published computer predictions by Trew *et al.* [5]. The method also has potential use for circuit diagnosis since the harmonics can be readily separated.

Both methods utilize magnetic field changes which could be obtained from small magnetic field-coils. These coils can be built to provide moderately fast tuning rates, suggesting that several tens of megahertz per microsecond is a distinct possibility. The ferrimagnetic resonator method requires an additional fixed magnetic field as indicated in Figs. 7, 8, and 9.

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REFERENCES

[1] B. H. Newton, "MIC TRAPATT oscillator for efficient *S*-band operation," *Electron. Lett.*, vol. 11 no. 14, p. 299, 1975.
[2] C. D. Corbey, B. H. Newton, and J. G. Summers, "Frequency stable MIC *S*-band and *C*-band pulsed TRAPATT oscillators," in *Proc. 5th European Microwave Conf.*, (Hamburg, Germany), 1975, p. 237.
[3] B. Glance, "A magnetically tunable microstrip IMPATT oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, June 1973, p. 425.
[4] S. G. Liu, "Magnetically tunable TRAPATT oscillator," in *Proc. 1974 IEEE Int. Solid State Circuits Conf.*, p. 98.
[5] R. Trew, G. Haddad, and N. Masnari, "Operation of *S*-band TRAPATT oscillators with tuning at multiple harmonic frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, p. 1043, Dec. 1975.
[6] R. Trew, "Properties of *S*-band TRAPATT diode oscillators," Ph.D. dissertation, Dep. Elec. Eng., Univ. of Michigan, 1975.
[7] W. von Aulock, *Handbook of Microwave Ferrite Materials.* New York: Academic, 1965.
[8] G. Winkler, "Substituted polycrystalline YIG with very low ferrimagnetic resonance linewidth and optical transparency," *IEEE Trans. Magn.*, vol. MAG. 7, p. 773, Sept. 1971.

Slots in Dielectric Image Line as Mode Launchers and Circuit Elements

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Abstract—**Slots in the ground plane of dielectric image lines are investigated using a planar resonator model. An equivalent circuit representation of the slot discontinuity is derived and the launching efficiency of the slot as a mode launcher is discussed. Slots are also demonstrated to be useful in the realization of dielectric image line array antennas.**

I. INTRODUCTION

IN RECENT years, several components for use in dielectric waveguide-integrated millimeterwave circuits have been developed. Semiconductor devices and their associated tuning and matching arrangements and especially mode launchers have been noted for their inherent radiation losses. To reduce the radiation effects in semiconductor circuits, metallic shielding is used (metal waveguide housing) and metal waveguide horn transitions are used as mode launchers [1]. A different approach to circumvent radiation losses uses periodic structures in the radiation-free stopband mode as tuning and matching devices [2], [3], or Yagi–Uda arrays as mode launchers [4].

In this paper slots in the ground plane of the dielectric image line are investigated for applications as mode launchers or discontinuity circuit elements. The main attraction of the proposed structure is that dielectric layer above the slots due to total reflection from the dielectric–air interface can act as a partial shielding, thus reducing radiation losses.

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